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XXVIII. Investigation of the Cause of that Indistinctness of Vision which has been ascribed to the smallness of the Optic Pencil. By William Herschel, LL.D. F.R.S.

Read June 22, 1786.

SOON after my first essays of using high powers with the Newtonian telescope, I began to doubt whether an opinion which has been entertained by several eminent authors, "that vision will grow indistinct, when the optic pencils are less than the 40th or 50th part of an inch," would hold good in all cases. To judge according to so rigid a criterion, I perceived that I was not intitled to see distinctly with a power much more than about 320, in a 7-feet telescope which bore an aperture of 6,4 inches; whereas in many experiments on double stars I found myself very well pleased with magnifiers that far exceeded such narrow limits. This induced me, as it were, by way of apology to myself, for seeing well where I ought to have seen less distinctly, to make a few experiments on the subject of the diameter of optic pencils. It occurred to me, that an opinion which limits them to any given size cannot be supported by theory, which does not determine on subjects of this nature, but must be decided, like many other physical questions relating to matters of fact, by careful experiments made upon the subject. The way, therefore, to come at truth, in a case which seemed to me of considerable importance, lay still open to me, as it had done to former ob-

servers; and I thought myself authorised, according to a Cartesian maxim (*Dubia etiam pro falsis habenda*), to suppose, for a while, the size of optic pencils, requisite for distinct vision, intirely undecided.

The first opportunity I had of making the proposed experiments was in the year 1778, and the result of them proved so decisive that I have never since resumed the subject; and had it not been for a late conversation with some of my highly esteemed and learned friends, I might probably have left the papers, on which these experiments were recorded, among the rest of those that are laid aside when they have afforded me the information I want. But a doubt seeming still to be entertained on the subject of the smallness of the optic pencils, it may now be proper for me to communicate these experiments, that it may appear how far the conclusions I have drawn from them are warranted by the facts on which I suppose them to rest.

Experiments with the naked eye.

Exp. 1. Through a very thin plate of brass I made a minute hole with the fine point of a needle; its magnified diameter, very accurately measured under a double microscope, I found to be ,465 of an inch, while under the same apparatus a line of ,05 in length gave a magnified image of 3,545 inches. Hence I concluded, that the real diameter of the perforation was about the 152d part of an inch. Through this small opening, held close to the eye, I could very distinctly read any printed letters on which I made the trial. Proper allowance must be made for the very inconvenient situation of the eye, which by the unusual closeness to the paper cannot be expected

to see with its common facility. Besides, the continual motion of the letters, which is required on account of the smallness of the field of view, must needs take up a considerable time.

Exp. 2. In some other pieces of brass I made smaller holes; and among many, that were measured with the same accuracy as in the former experiment, I found one whose magnified diameter was ,29: hence the real diameter could not exceed the $\frac{1}{244}$ th part of an inch. Through this opening I could also read the same letters; but the difficulty of managing so as not to intercept all the incident light, as well as the very uneasy situation of the eye, were sufficient reasons for not carrying the intended experiments any further under this form. Besides, I should hardly have allowed them to be fair, if, on a further contraction of the hole in the brass plate, an indistinctness had come on; as we might well have suspected at least two other causes, besides the smallness of the pencils, to contribute to such an imperfection; viz. want of light, and a deflection of it on the contracted edges of the hole.

Microscopic Experiments.

Exp. 3. I had now recourse to a double microscope, consisting, for simplicity's sake, of only two lenses. The focal length of the eye-glass, carefully ascertained by an object half a mile off, being ,9; the distance of the object-glass from the eye-glass 9,36; and the aperture of the object-glass ,0405. Hence we compute that the diameter of the optic pencil, when it entered the eye, could not exceed the $\frac{1}{232}$ d part of an inch; yet with this construction I saw very distinctly every object I placed under the microscope.

Exp.

Exp. 4. I reduced the aperture of the object-glass to ,013; hence the pencil was found to be the 724th part of an inch; and yet I saw with this construction very distinctly every object that was placed under the magnifier.

Exp. 5. I made a second reduction of the aperture of the object-glass, so that now it was no more than ,0052; and therefore the optic pencil less than the 1800th part of an inch; and yet I could very well count the bristles on the edge of the wing of a fly, and distinguish their length and thickness.

Exp. 6. Changing the construction of the microscope, I now reduced the pencils by an increase of power. Solar focus of the eye-glass ,52; distance between the object-glass and eye-glass 7,6; aperture the same as in the third experiment. This gave me a pencil of the 336th part of an inch, with which I saw very distinctly.

Exp. 7. Applying now the reduced aperture of the fourth experiment, I had a pencil of the 1139th part of an inch, with which I saw very well.

Exp. 8. I changed the eye lens for another of ,171 focal length; the object-glass and distance between the two lenses remaining as in the two last experiments; aperture ,02. This gave a pencil of the 2173d part of an inch, with which I could count, or rather successively see, the bristles before-mentioned very well; the field, on account of the great power, not taking in more than two large and a small one at a time.

Exp. 9. I was now convinced, that we may see distinctly with pencils incomparably less than the 40th or 50th part of an inch; and indeed so far from expecting any obstruction to distinct vision from the smallness of the pencils, it appeared to me now as if their size might in future be entirely left out of the account. With a view, however, of seeing what other

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cause might bring on that indistinctness which had been ascribed to the smallness of the optic pencils, I continued these experiments with a variation in the apparatus, and used now an object lens of a different focal length; the aperture and other particulars being as in the 4th experiment. By this construction, which gave me a pencil of the $\frac{724}{1}$ th part of an inch, I could see objects very well; but though they appeared distinctly, they were not so sharp on the edges as one would wish to see them. This being compared with the 4th experiment, it appeared that, with equal pencils, unequal degrees of distinctness may take place; and a pretty striking circumstance, which served to lead me in the following experiments, was, that the smallest power gave me the least distinct image; notwithstanding, from former trials, the goodness of the lenses I employed could not be doubted.

Exp. 10. On an examination of circumstances it occurred to me, as indeed I had already before surmised, that a certain proportion of aperture might be necessary to a given focal length of an object-lens or speculum; and that a failure in this point might probably bring on that indistinctness which had been ascribed to the smallness of the pencils. In order, therefore, to put this to a trial, I used now an object-lens of 1,25 focal length, with an aperture confined to .01; the rest of the apparatus being as in the 3d, 4th, and 5th experiments. The pencil in this case was about the $\frac{1000}{1}$ th part of an inch; and though by a different construction I had already seen very well with a pencil of not half that diameter, I found this to give me, as now I had reason to expect, a very indistinct picture, so much so indeed, that it could hardly be called a representation of the object.

Exp,

Exp. 11. Increasing the aperture of the object-lens to ,0124, I had a pencil of the 758th part of an inch, but could see no better with it.

Exp. 12. Proceeding in the track now pointed out to me, I admitted an aperture of ,017, which gave a pencil of the 550th part of an inch, but could see not much better with it than before.

Exp. 13. On a farther increase of the aperture to ,0231, and a pencil of the 406th part of an inch, I saw a little better; but still had not distinctness enough even to see the bristles before-mentioned at all. Hence we may conclude, that, in such constructions as the present one, the aperture of the object-glass must bear a considerable proportion to its focal length; since the 54th part (for ,0231 : 1,25 :: 1 : 54) is here not nearly sufficient.

Exp. 14. To the same apparatus I applied a higher power, by an exchange of the eye-glass; but the indistinctness remained as before.

Exp. 15. Returning again to the former construction, I admitted an aperture of about ,037; and having now a pencil of nearly the 250th part of an inch, I could but just perceive some of the large bristles, which shews that even the 34th part (for ,037 : 1,25 :: 1 : 34) of the focal length is not a sufficient aperture for object-lenses that act under such circumstances as the present.

So far I have only related experiments that were made in the year 1778; and my opinion that the smallness of the optic pencils could be no objection to seeing well being thus supported by evident facts, I hesitated not, in a Paper on the Parallax of the Fixed Stars (Phil. Transf. vol. LXXII. p. 96.) to affirm, that we might see distinctly with pencils much smaller

smaller than the 40th or 50th part of an inch. It did not appear to be necessary, nor would the subject of that Paper permit me to enter into a detail of experiments; but having, in the course of my reading about that time, met with an account of some very small globules made for microscopic uses, I contented myself with an instance of small pencils taken from them. I shall, however, now proceed just to hint at a few inferences that may be drawn from these related experiments; as, upon a mature consideration, we may find reason to believe they point out a cause of indistinctness of vision hitherto never noticed by optical writers; and which, when properly investigated, cannot but influence, and in some respects contribute to the improvement of, our theories in optics. For, admitting that every object-glass or speculum, whose aperture bears less than a certain ratio to its focal length, will begin to give an indistinct picture, it will follow, that while former opticians have been endeavouring to diminish the aberrations arising from the spherical figure, and the different refrangibility of rays, by increasing the focal length, they have been unaware of exposing themselves to the consequences of the cause of indistinctness here pointed out. And till its influence shall be well ascertained and brought to a proper theory, we must suspect that such tables as those which are given in our best authors of optics, pointing out an aperture of less than 6 inches for a glass of 120 feet focal length (or a ratio of 1 to 20) must be far from having that degree of perfection which may yet be obtained. No wonder that telescopes, made according to theories or tables, where one of the causes of indistinctness is unsuspected, and therefore left out of the account, can bear no smaller pencil than the 40th or 50th part of an inch! If then, on one hand, by increasing our apertures we

certainly

certainly run into great imperfections, we ought nevertheless also to consider what dangers, on the other, we may incur by lessening them too much.

As soon as convenient, I intend experimentally to pursue this subject, in order to obtain proper *data* for submitting this cause of optical imperfection to theory; at present my engagement with the work of a 40-feet reflector will hardly permit so much leisure; and till I shall have repeated, extended, and varied these experimental investigations, I would wish them to be looked upon as mere hints that may afford matter for future disquisitions to the theoretical optician.

